Measurement of the CCQE axial mass with the SciBar detector of K2K

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Outline

- Theoretical framework
- SciBar detector
- Event Selection
- Analysis
- Results

Theoretical framework

- The CCQE cross-section can be written as:

$$\frac{d\sigma^{\nu\bar{\nu}}}{dq^2} = \frac{M^2 G_F^2 \cos^2\theta_c}{8\pi E_\nu^2} \cdot \left[A(q^2) \mp \frac{(s-u)B(q^2)}{M^2} + \frac{C(q^2)(s-u)^2}{M^4}\right],$$

- for neutrinos and + for antineutrinos.

$$A(q^2) = \frac{m^2 - q^2}{4M^2}\left[\left(4 - \frac{q^2}{M^2}\right)\right]|F_A|^2 - \left(4 + \frac{q^2}{M^2}\right)|F_V^1|^2 - \frac{q^2}{M^2}|\xi F_V^2|^2\left(1 + \frac{q^2}{4M^2}\right) - \frac{4q^2 ReF_V^1 * \xi F_V^2}{M^2}$$

$$B(q^2) = -\frac{q^2}{M^2 ReF_A * (F_V^1 + \xi F_V^2)}$$

$$C(q^2) = \frac{1}{4}\left(|F_A|^2 + |F_V^1|^2 - \frac{q^2}{M^2\left|\frac{\xi F_V^2}{2}\right|}\right)$$

Theoretical framework

- For that we have assumed:
  - Time reversal invariance and charge symmetry:
    - $F_s = F_T = 0$ (scalar and tensor terms)
  - Partially conserved axial current :
    - Small (~5%) F_p (pseudoscalar) term
- Conserved Vector Current hypothesis allows to relate the vector current in neutrino interactions to that of the electron scattering data.

Theoretical framework

- From CVC we can relate $F^{1,2}_V$ form factors to the isovectors Sach electric and magnetic form factors G_E and G_M that are determined experimentally.
- They are related to the neutron and proton electric and magnetic moments,

$$F_V^1(q^2) = \frac{G_E^V(q^2) - \frac{q^2}{4M^2} G_M^V(q^2)}{1 - \frac{q^2}{4M^2}}$$

$$\xi F_V^2(q^2) = \frac{G_M^V(q^2) - G_E^V(q^2)}{1 - \frac{q^2}{4M^2}}$$

$$G_E^V(q^2) = G_E^p(q^2) - G_E^n(q^2)$$

$$G_M^V(q^2) = G_M^p(q^2) - G_M^n(q^2)$$

Theoretical framework

- $G_E^{p,n}$ and $G_M^{p,n}$ can be expressed in different ways:
  - Dipole approximation:

$$G_D(q^2) = \frac{1}{\left(1 - \frac{q^2}{M_V^2}\right)}$$

$$G_E^p = G_D(q^2),\ G_E^n = 0\ G_M^p = \mu_p G_D(q^2)\ ,\ G_M^n = \mu_n G_D(q^2)$$

  - BOSTED parametrization

$$\frac{G_{Mn}(q^2)}{\mu_n^{-1}} = (1 - 0.74q + 9.29q^2 - 7.63q^3 + 4.63q^4)^{-1}$$

$$\frac{G_{Mp}(q^2)}{\mu_p^{-1}} = (1 + 0.35q + 2.44q^2 + 0.50q^3 + 1.04q^4 + 0.34q^5)^{-1}$$

  - BBA

$$G^N_{E,M}(Q^2) = \frac{G^N_{E,M}(Q^2=0)}{1 + a_2Q^2 + a_4Q^4 + a_6Q^6 + \ldots}$$

Factor	a_2	a_4	a_6	a_8	a_{10}
G_E^p	3.253	1.42	0.085	0.33	-9.3E-2
G_M^p	3.104	1.42	0.11	-6.9E-3	3.7E-4
G_E^p	3.043	0.85	0.68	-0.12	8.9E-3

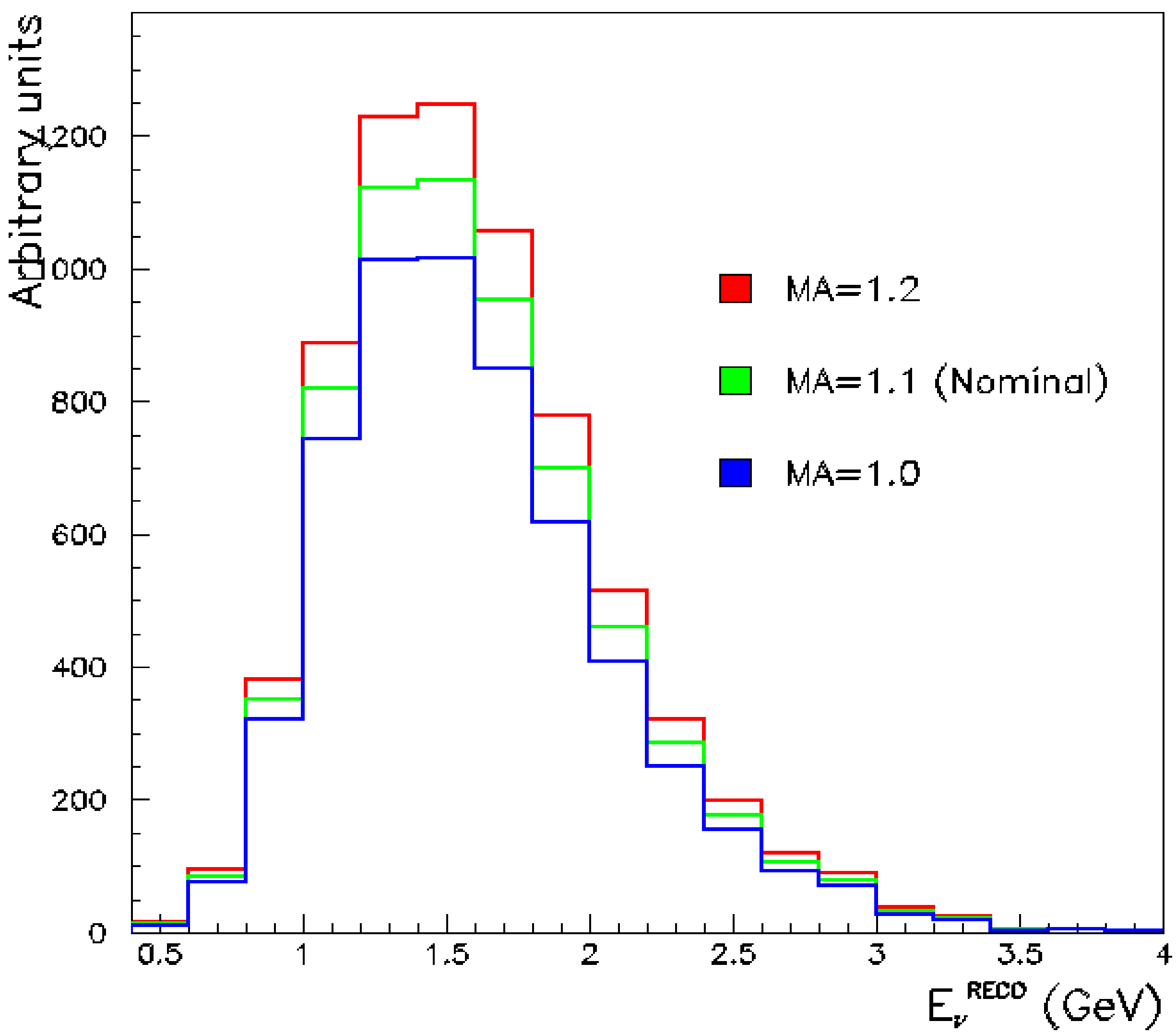
Theoretical framework

- The axial form factor is assumed to follow the dipole approximation

$$F_A(q^2) = \frac{F_A(0)}{(1+q^2/M_A^2)^2}$$

- Where $F_A(0)$ is determined experimentally from β decays, -1.267

Theoretical framework

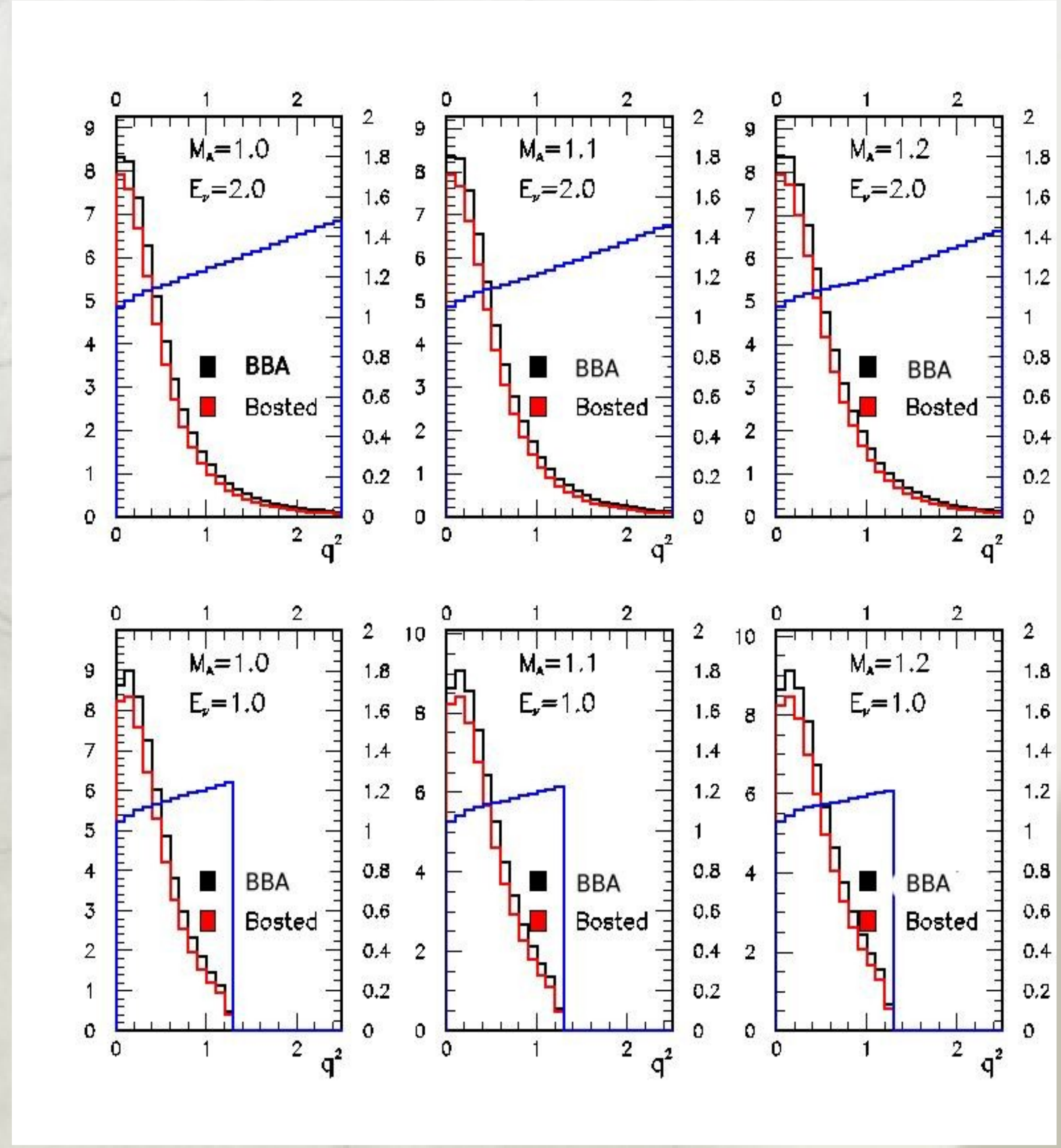


Effects of M_A

- Change total cross-section.
- Deforms the q^2 distribution

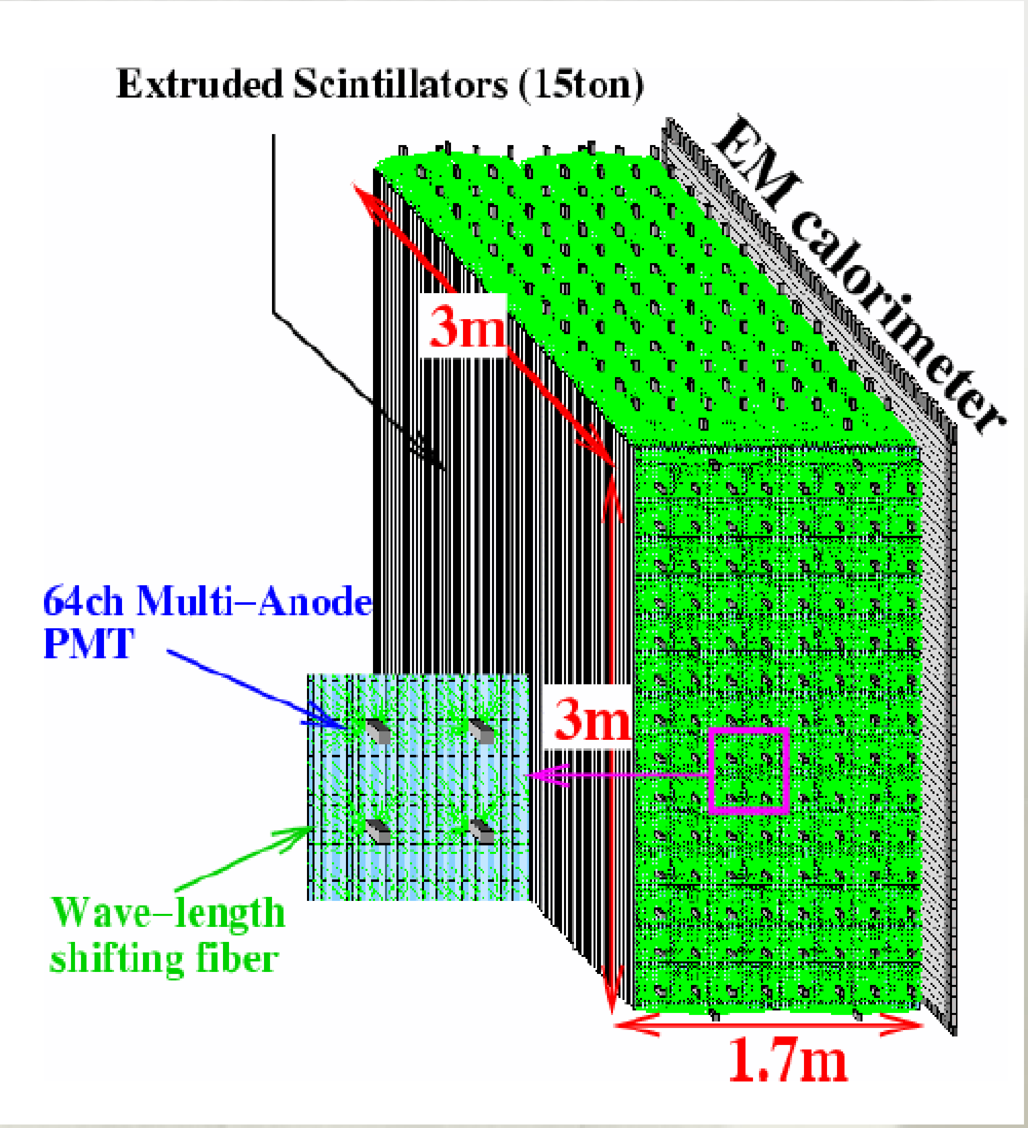
Theoretical framework

- Different vector form factors alter the result.



SciBar detector

- Fully active scintillator tracker. XZ & YZ projective bars.
- 15 tons of total mass.
- Fine segmentation:
  - $300 \times 2.3 \times 1.6$ cm^3
  - 15000 channels
  - Readout by MPMT.
- Complemented by EM. Calorimeter and Muon Range Detector (MRD).
- See A.Rodriguez talk for more details.



Event Selection

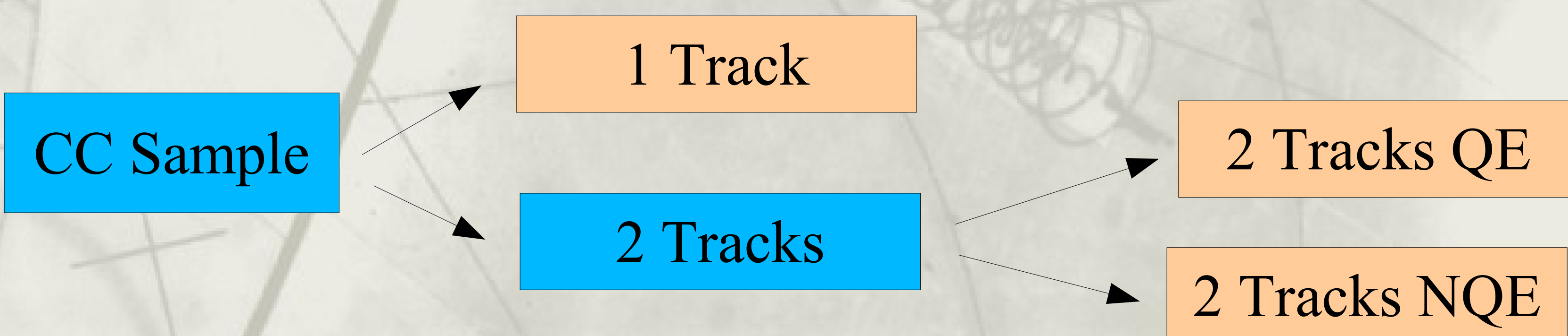
- We use events with at least one muon (1 layer and more in MRD) in the SciBar fiducial volume:

1. $|VTX_x^{initial}| < 130cm$
2. $|VTX_y^{initial} + 9.7| < 130cm$
3. $207 - 9 < VTX_z < 343cm$

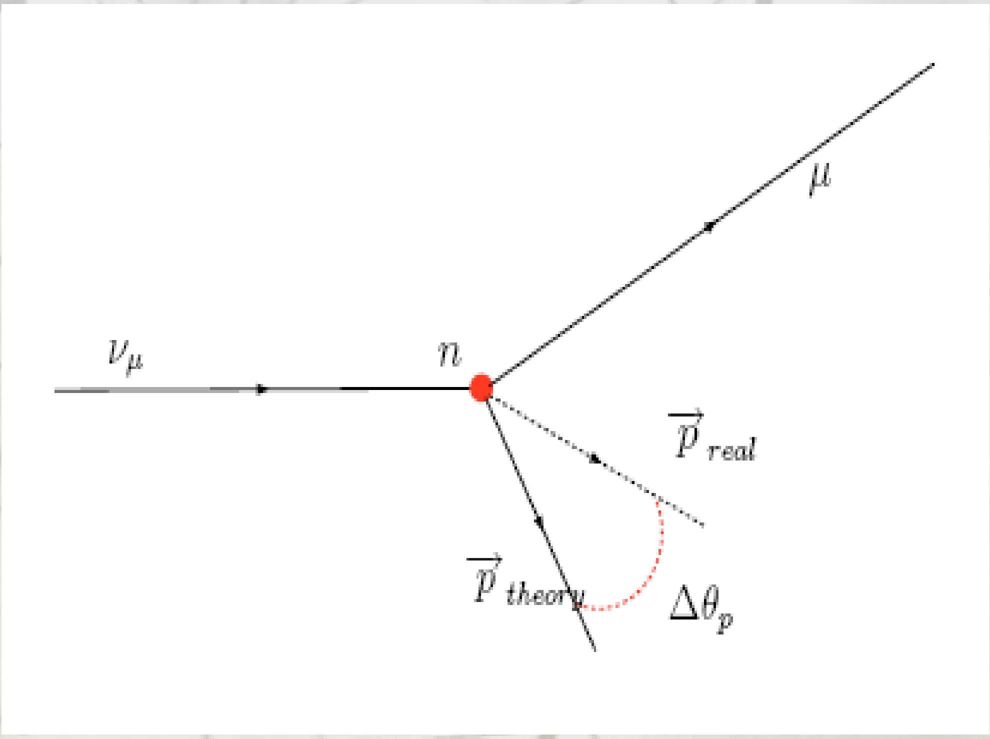
- Muon should be during the spill: time < 1250 ns.

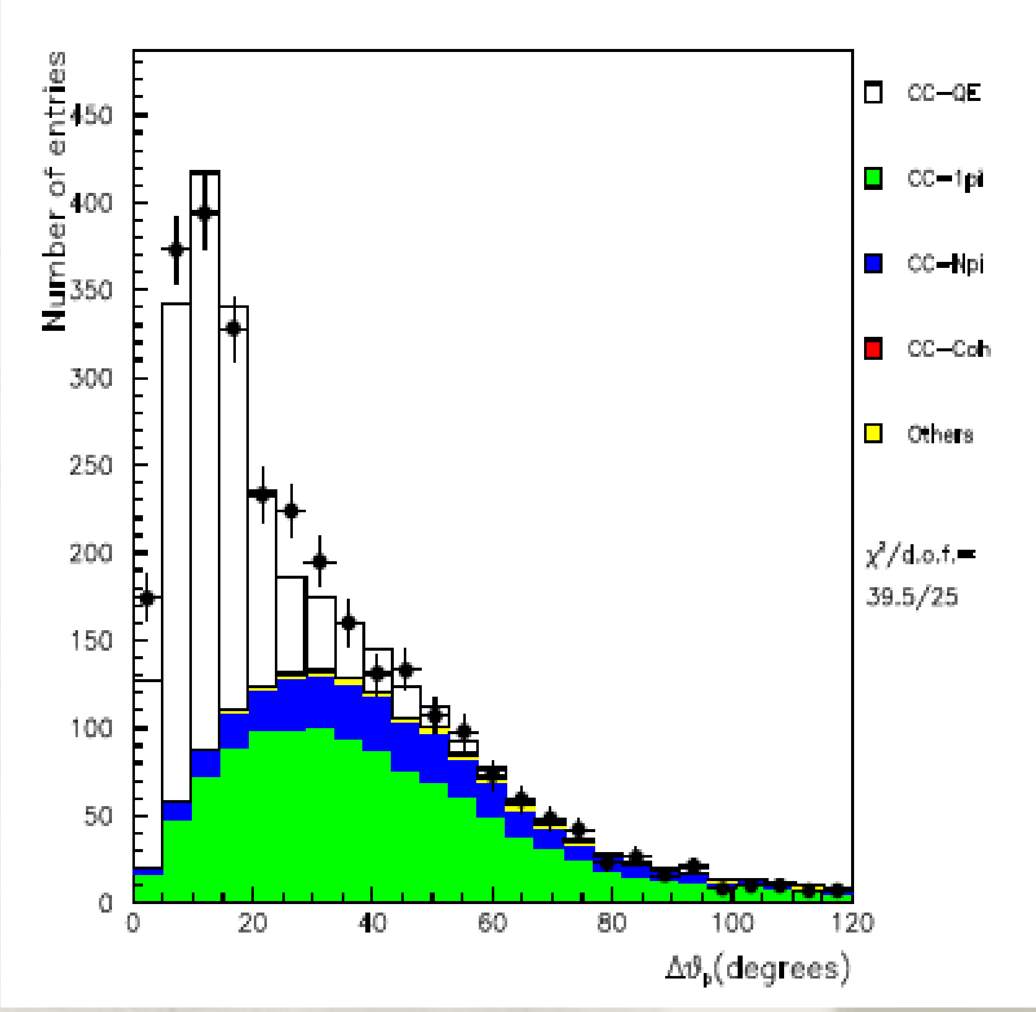
Event Categories

- Events are classified as follow:
  - 1 single muon track (SciBar track matched to MRD object).
  - 2 tracks with a common vertex: within a box of 4.5cm around the muon vertex and synchronous to the muon track(<100ns).
- The 2 track events are then subdivided in QE and NQE according to the $\Delta\theta_p$ angle:
  - $\Delta\theta_p < 20^o$ QE and $\Delta\theta_p > 20^o$ NQE



Event Categories: $\Delta\theta_p$





Event reconstruction

- The samples have different purities on CCQE:

Sample	$q^2 > 0.0$	Pur.	$q^2 > 0.2$	Pur.
1-Track	7405	54%	4032	59%
2-Track QE	1264	77%	1142	80%
2-Track nonQE	1537	19%	923	28%
Total	10206	52%	6097	59%

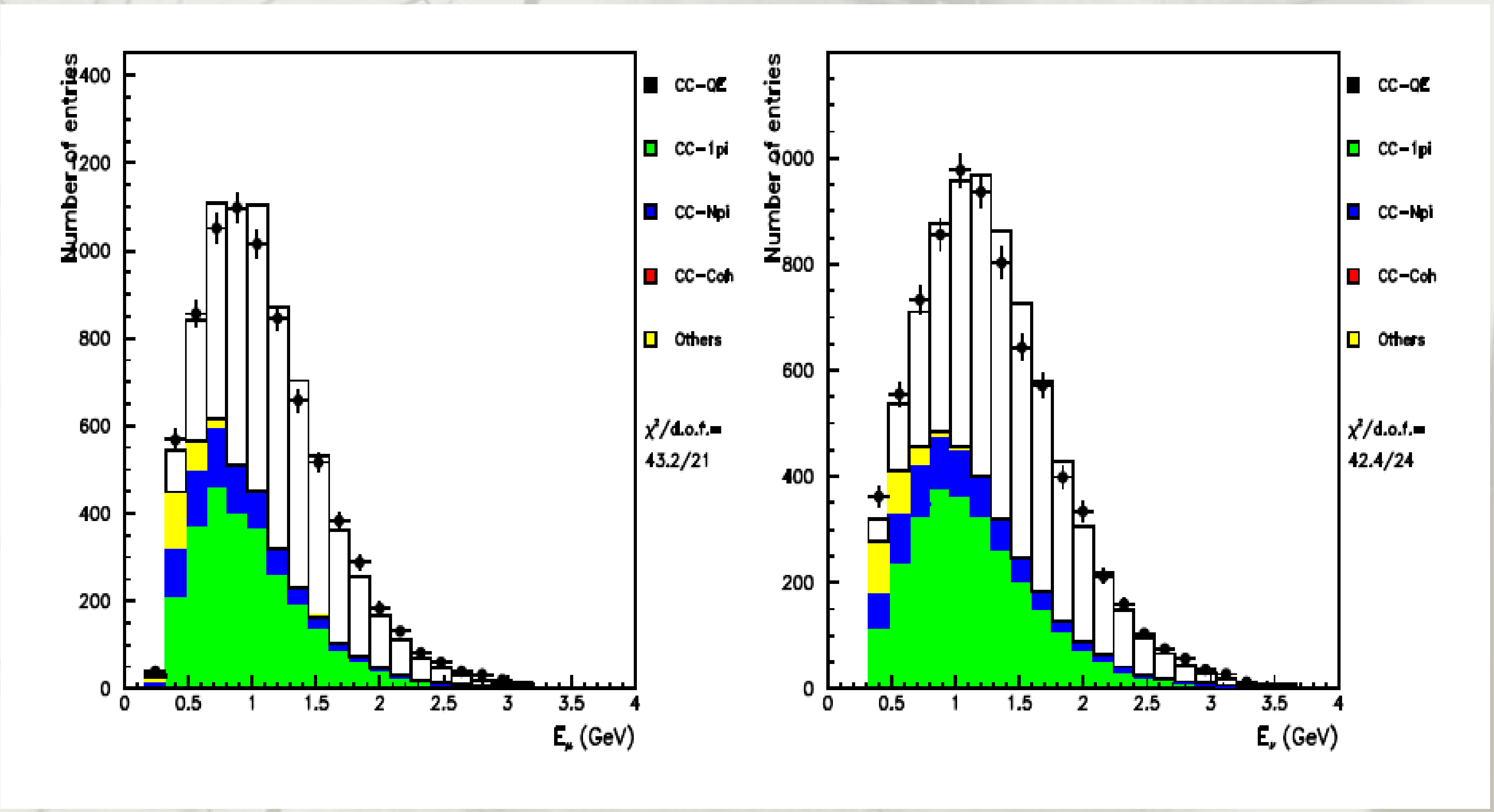
- All samples are used in the Analysis to constrain several MC properties:
  - Neutrino flux, ratio of CCQE to other interactions, etc...

Event reconstruction

- Event properties are reconstructed assuming CCQE and nucleon target at rest.
- We obtain for each event the neutrino energy and the $|q^2|$ value.

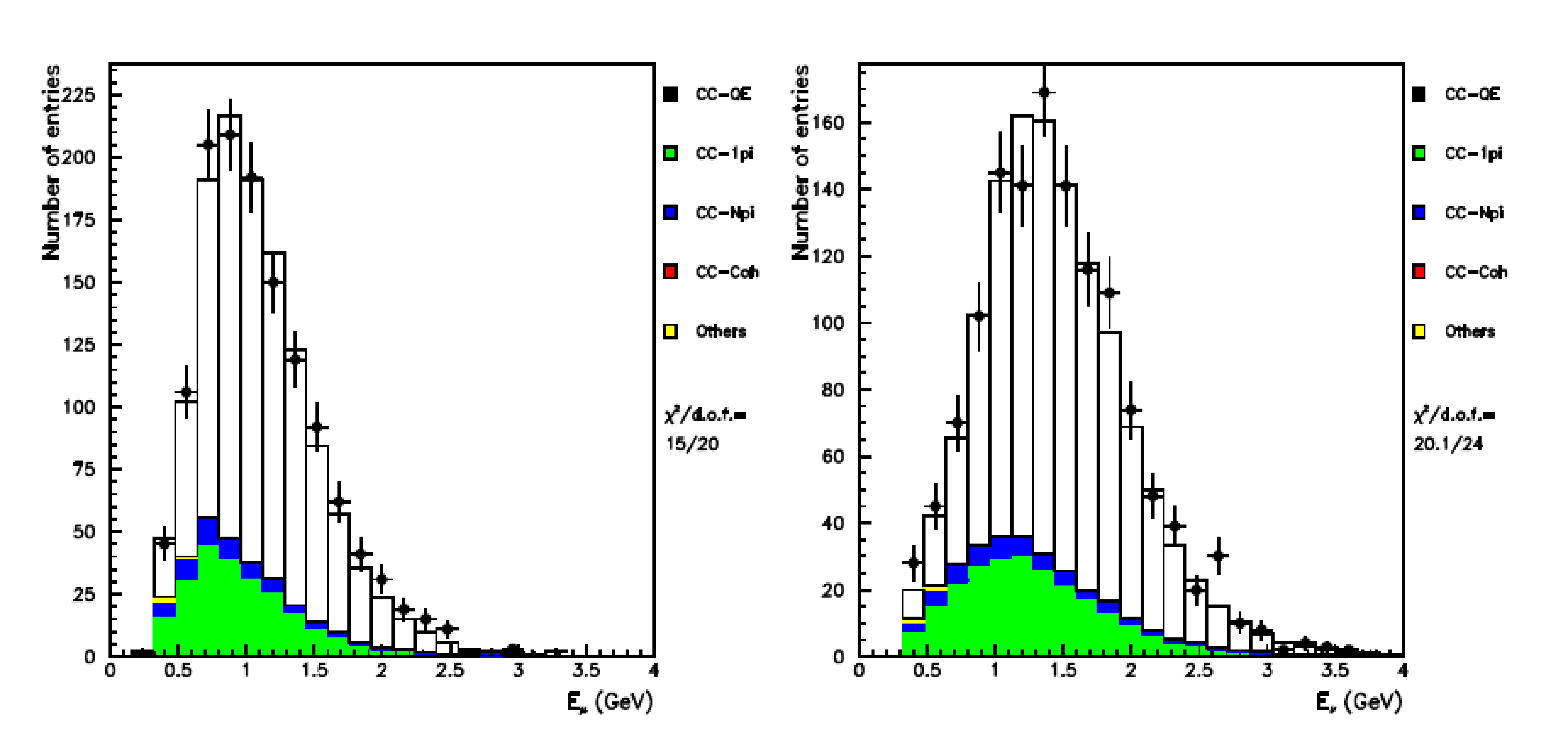
Event reconstruction

Muon and neutrino energy for single track events



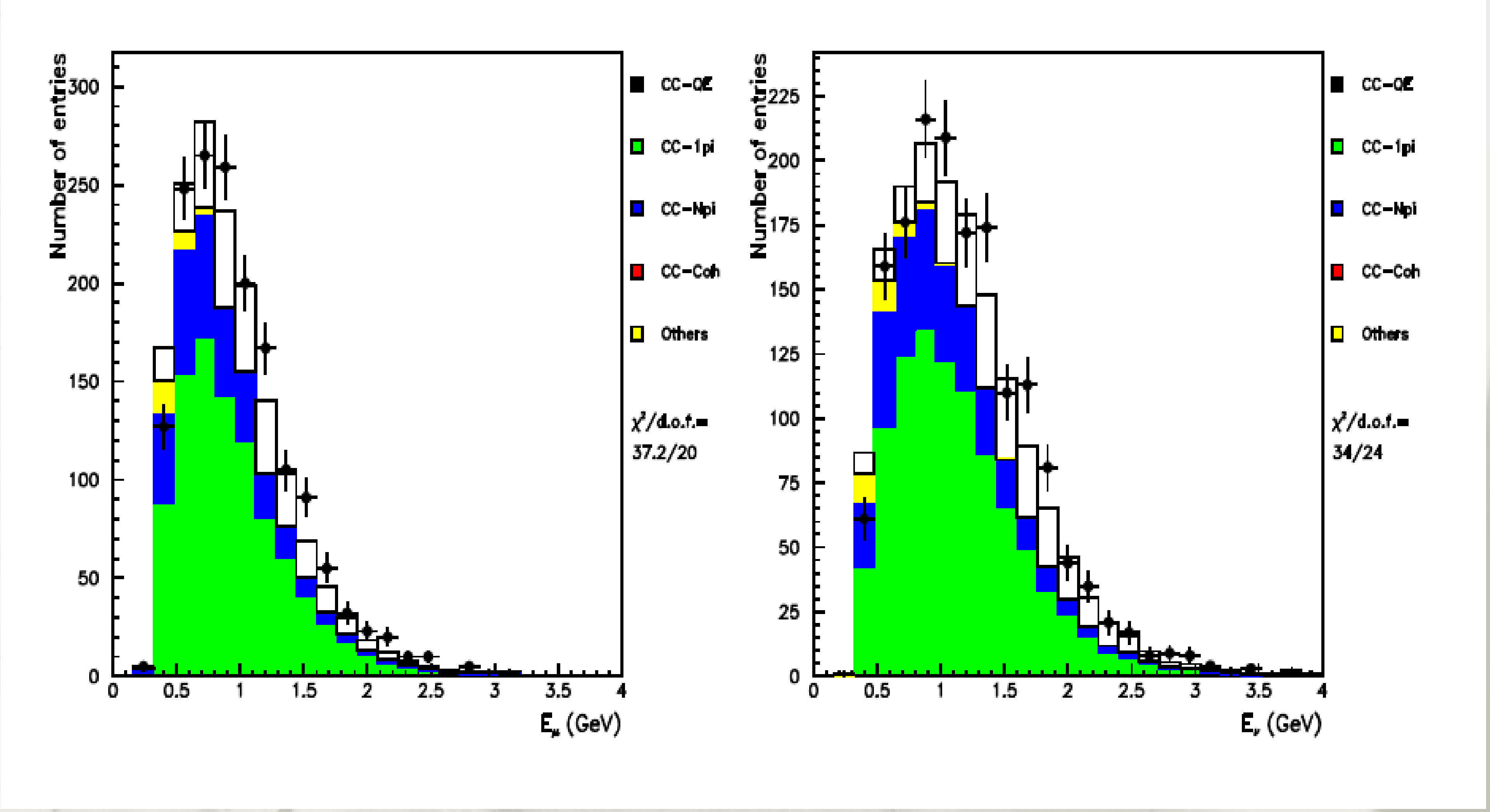
Event reconstruction

Muon and neutrino energy for 2 track QE events



Event reconstruction

Muon and neutrino energy for 2 track NQE events



Analysis

- To obtain the different MC templates for comparison, the MC events are reweighted as:

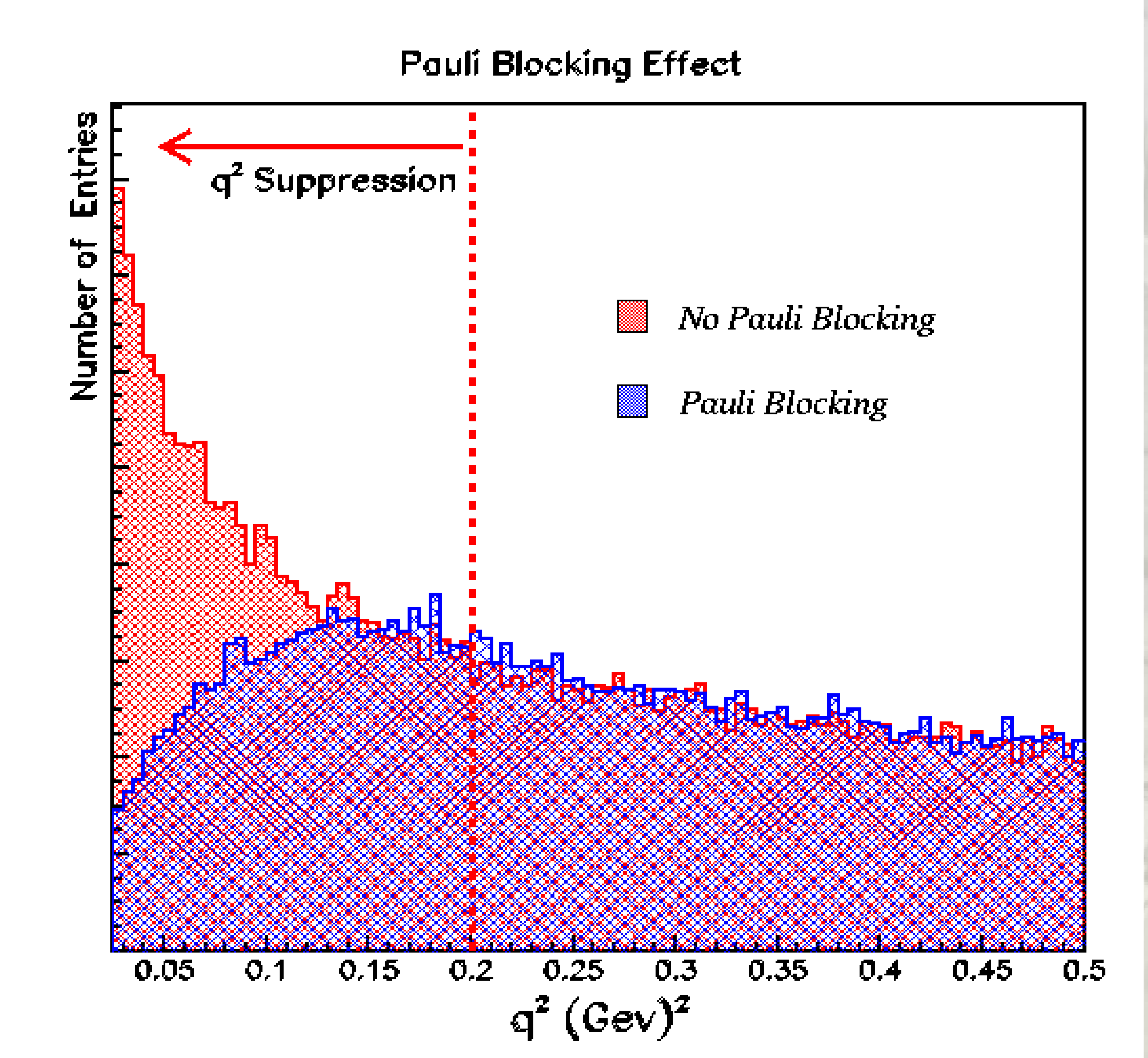
$$Weight = \frac{Cross\,Section(M_A)}{CrossSection(M_A^{nominal})}$$

- Fermi motion is taken into account in the MC and reweighting factors.

Analysis

- We bin the data
  - in 5 bins of energy following the beam pion monitor (PIMON) bins.
    - [0.5-1.0], [1.0-1.5],[1.5-2.0],[2.0-2.5][2.5-]
    - We will fit them together with M_A with the corresponding flux constrain.
    - There is no bias because the flux constrain is not based on neutrino interactions.
  - and 12 q^2 bins from 0. to 2.4 GeV.

Analysis: Pauli blocking



The low q^2 is highly affected by Pauli-blocking.

The analysis will be done removing values below 0.2.

The first q^2 bin is ignored in the fit.

Analysis: Monte Carlo

- The fit is done using the likelihood:

$$\mathcal{L} = \prod_s \prod_i \frac{e^{-\mu_i^s} (\mu_i^s)^{n_i^s}}{n_i^s!}$$

s is the sample 1Tr, 2TrQE, 2TrNQE
i is the bin of q^2 and neutrino energy

- where $\mu_i^s = s_i^s + b_i^s$, and

$$s_i^s = \mathcal{N} \cdot \frac{\sigma(q^2_{true}; M_A)}{\sigma(q^2_{true}; M_A^{Nominal})} \cdot \phi(E_\nu) \cdot N^s_{QE}(q^2_{reco,i})$$

$$b_i^s = \mathcal{N} \cdot f^{nQE/QE} \cdot \phi(E_\nu) \cdot N^s_{NQE}(q^2_{reco,i})$$

- n_i^s is the number of events in the data

Analysis: Monte Carlo

$$s_i^s = \mathcal{N} \cdot \frac{\sigma(q^2_{true}; M_A)}{\sigma(q^2_{true}; M_A^{Nominal})} \cdot \phi(E_\nu) \cdot N^s_{QE}(q^2_{reco,i})$$

Number of QE events in MC in reconstructed energy and q^2

M_A reweight

Flux reweight

Number of NQE events in MC in reconstructed energy and q^2

Data/MC normalization

$$b_i^s = \mathcal{N} \cdot f^{nQE/QE} \cdot \phi(E_\nu) \cdot N^s_{NQE}(q^2_{reco,i})$$

$\sigma_{nqe} / \sigma_{qe}$ correction factor

Analysis

- And construct the log-likelihood:

$$\mathcal{L} = \mathcal{L}_{MA}(q^2, E_i) + \mathcal{L}(\phi[\mathcal{E}_\nu]) = \sum_s \sum_i \left[(b_i^s + s_i^s(\alpha) - n_i^s) + n_i^s ln \frac{n_i^s}{b_i^s + s_i^s(\alpha)} \right] + \mathcal{L}(\phi[\mathcal{E}_\nu])$$

- $L(\phi(E_\nu))$ is the gaussian constrain from PIMON neutrino flux data.
- And

$$n_i^{1tr} \rightarrow n_i^{1tr}$$

$$n_i^{2trQE} \rightarrow R_{1tr/2tr} n_i^{2trQE}$$

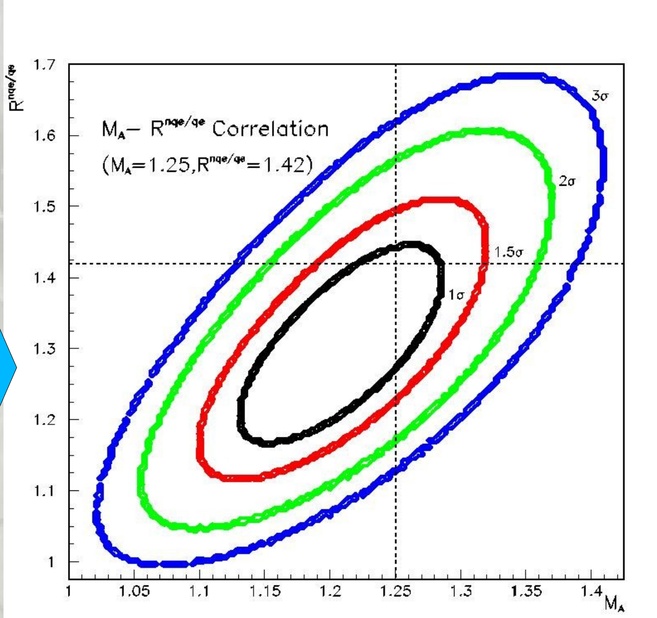
$$n_i^{2trNQE} \rightarrow R_{1tr/2tr} R_{2trNQE/2trQE} n_i^{2trNQE}$$

Analysis

- We allow the following variables to float in the fit:
  - Overall normalization.
  - M_A
  - $f^{nqe/qe}$, ratio of NQE to QE cross-sections
  - $R^{2tr/1tr}$, ratio of 2tr and 1tr samples
  - $R^{2trNQE/2trQE}$, ratio of 2tr NQE and 2tr QE
  - 4 Energy bins gaussian constrained by PIMON result.

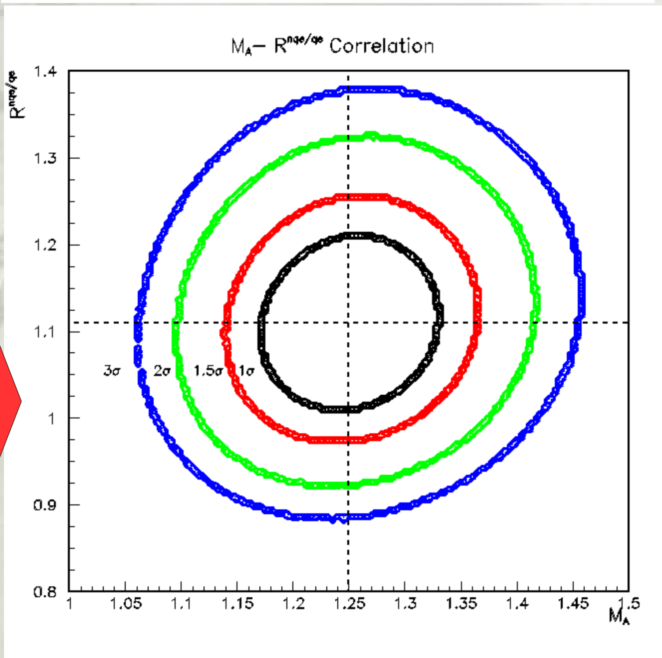
Analysis: fit parameter $f^{NQE/QE}$

- $f^{nqe/qe}$ is closely related to the fitting:
  - a) change in M_A implies a change in the cross section
  - b) $f^{nqe/qe}$ increases to compensate the effect of the cross section rising
- Hence as M_A, the $f^{nqe/qe}$ increases as well.



- To avoid this effect the $f^{nqe/qe}$ is separated in two terms:
  - Cross section effect (R^σ)
  - 2-Shape change caused by M_A ($R^{nqe/qe}$)
- $f^{nqe/qe'} = R^\sigma R^{nqe/qe}$

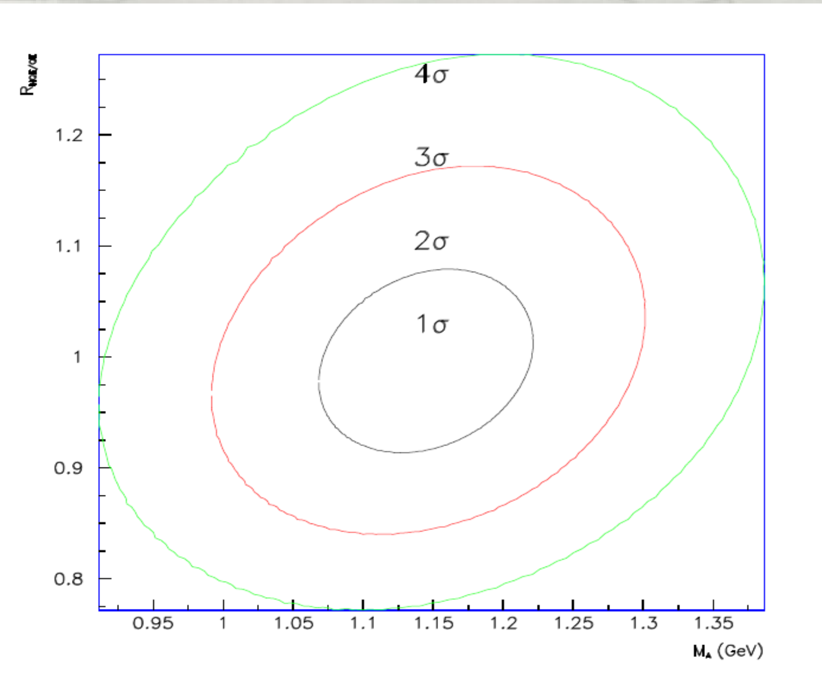
$$R^\sigma = \frac{f(M_A)^{QE}}{f(M_A(Nominal))^{QE}} \qquad f(M_A) = \int \phi(E)\sigma_{ccqe} dq^{2} dE$$



We will use $R^{nqe/qe}$ from now on....

Results

- After the fit the results are:
  - **BBA :** $M_A = 1.144$ +- 0.077 $R^{nqe/qe} = 0.993$ +- 0.083 χ^2/ndof= 118.67/105
  - **BOSTED :** $M_A = 1.152$ +- 0.078 $R^{nqe/qe} = 0.994$ +- 0.083 χ^2/ndof= 118.80/105
  - **DIPOLE:** $M_A = 1.219$ +- 0.076 $R^{nqe/qe} = 0.998$ +- 0.083 χ^2/ndof= 118.57/105
- We will discuss from now the results based on BBA vector form factor as default result of the analysis.



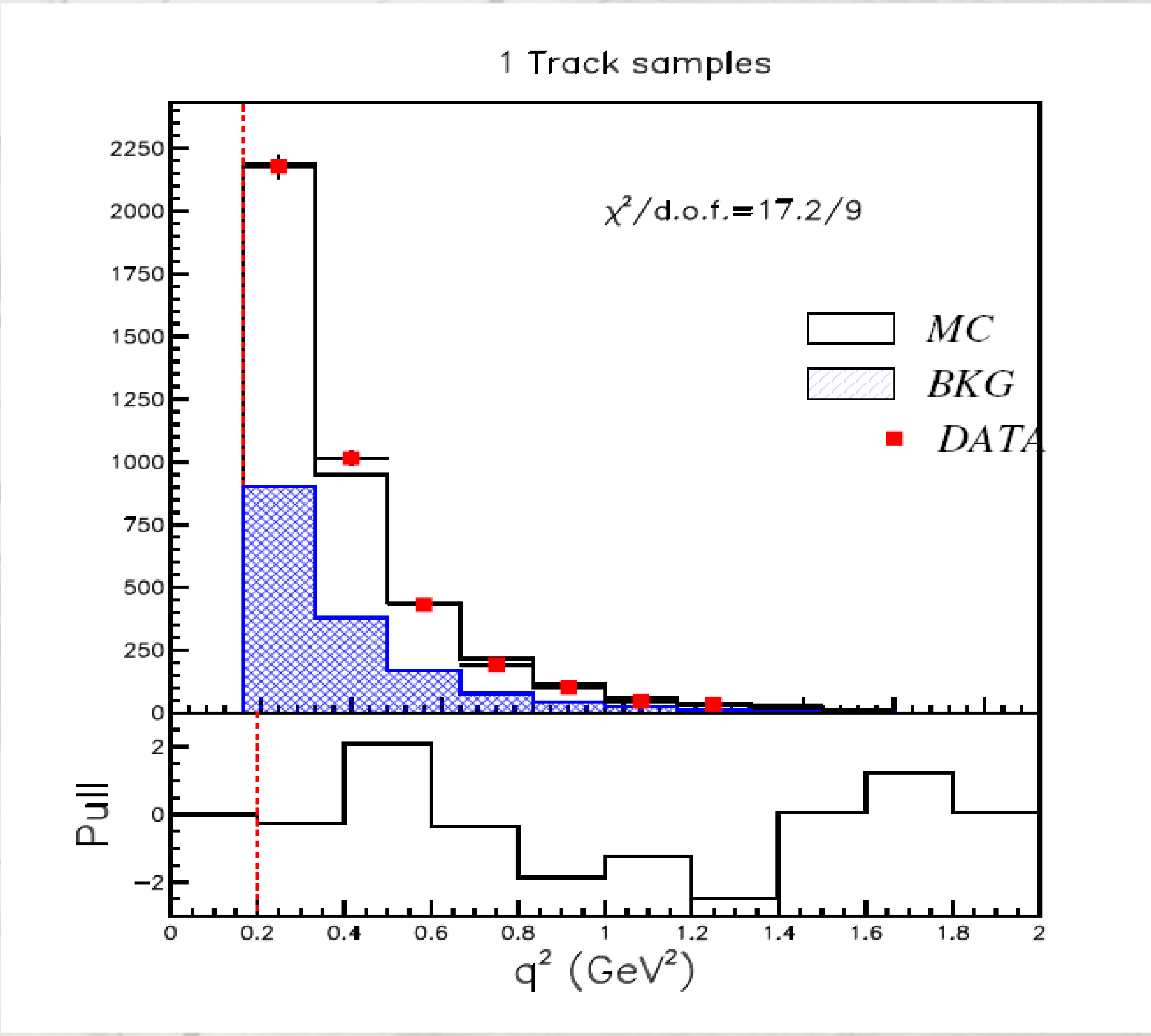
Results

- The result of the flux normalization is also consistent with previous analysis:

Energy Bin	PIMON	BBA	BOSTED	DIPOLE	Global Fit
0.5-1.0	-	1.20 ± 0.06	1.20 ± 0.06	1.20 ± 0.06	1.154 ± 0.61 (0.75-1.0)
1.0-1.5	1.0	1.0	1.0	1.0	1.0
1.5-2.0	$0.941^{+0.11}_{-0.099}$	0.94 ± 0.06	0.94 ± 0.06	0.94 ± 0.06	0.911 ± 0.044
2.0-2.5	$0.945^{+0.12}_{-0.18}$	0.98 ± 0.08	0.98 ± 0.08	0.97 ± 0.08	1.069 ± 0.059
2.5–	$1.059^{+0.48}_{-0.34}$	1.41 ± 0.12	1.40 ± 0.12	1.40 ± 0.12	1.152 ± 0.142 (2.5-3.0)

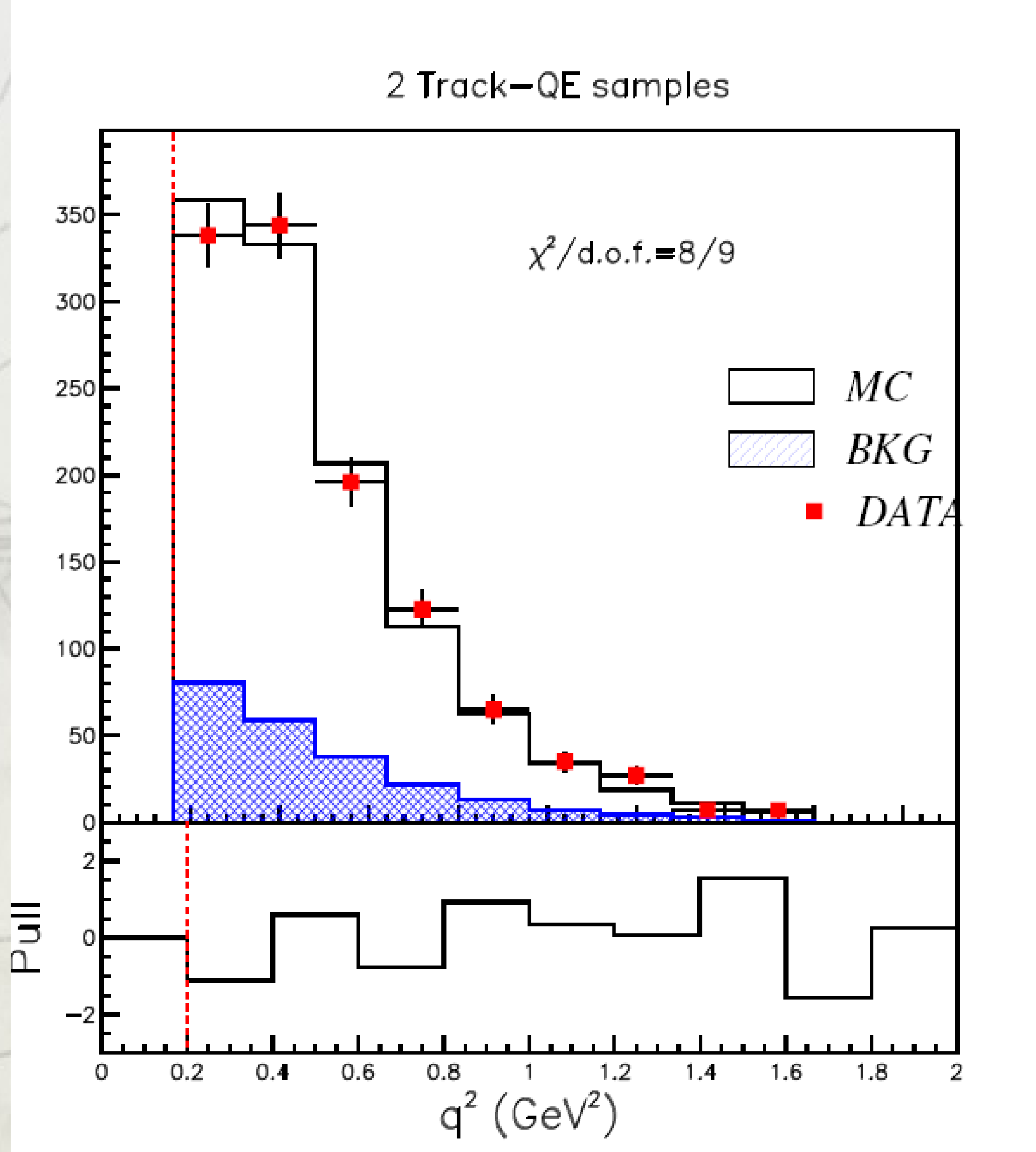
Systematic checks

- q^2 distributions after the fit



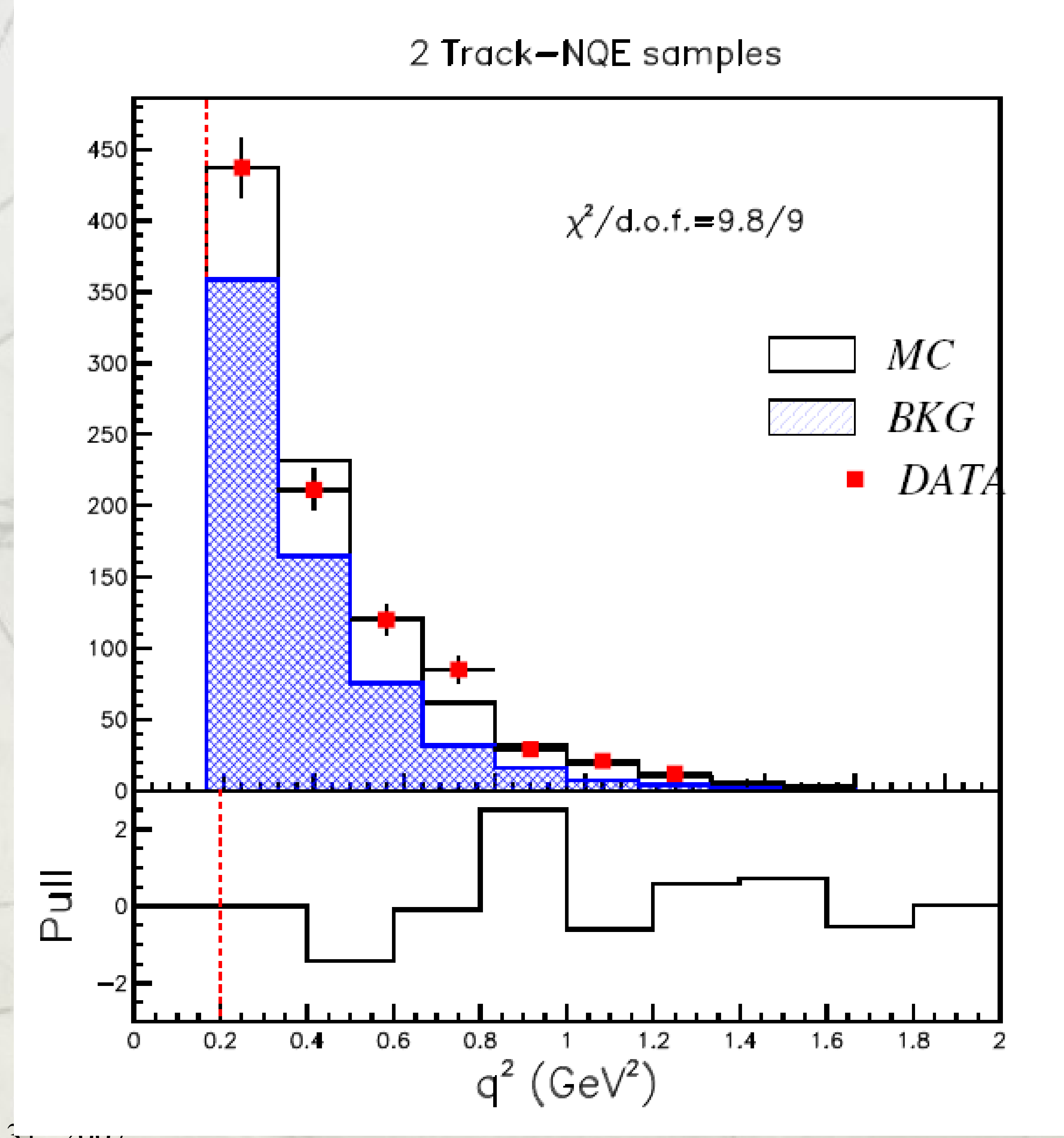
Systematic checks

- q^2 distributions after the fit



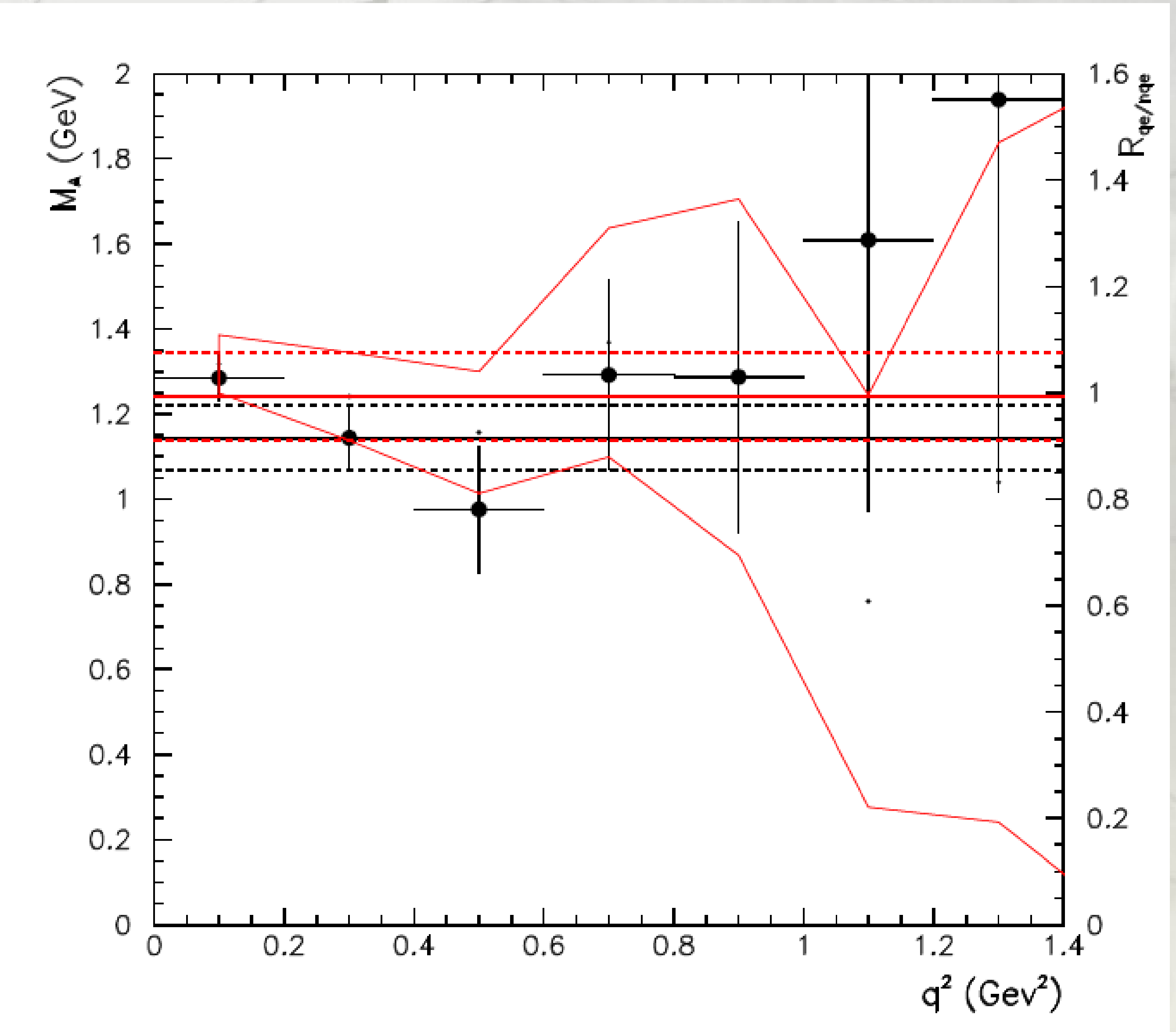
Systematic checks

- q^2 distributions after the fit



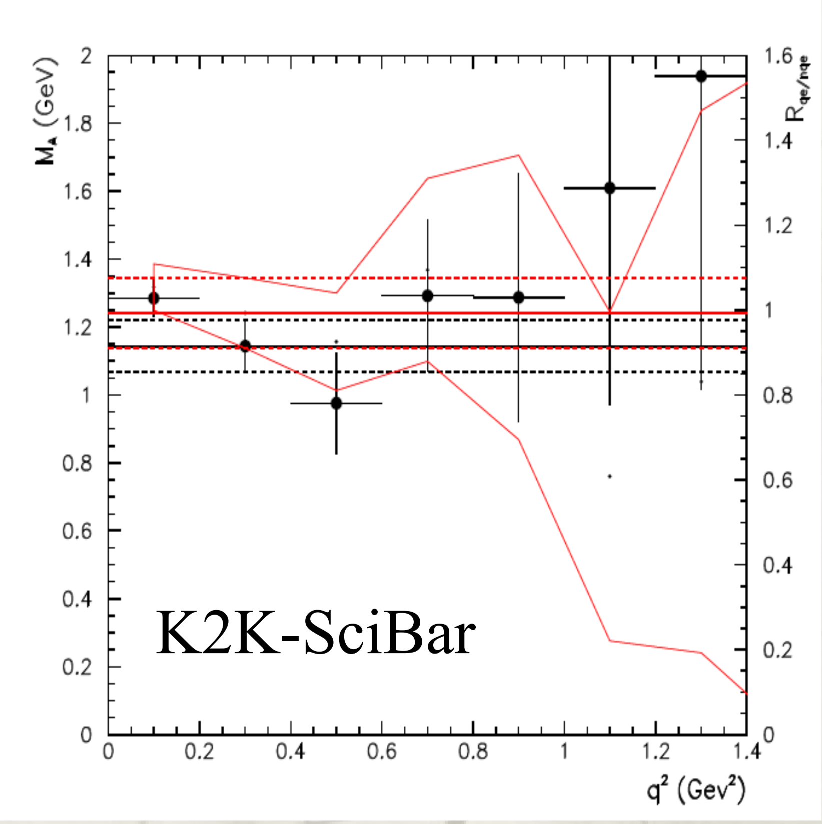
Systematic checks

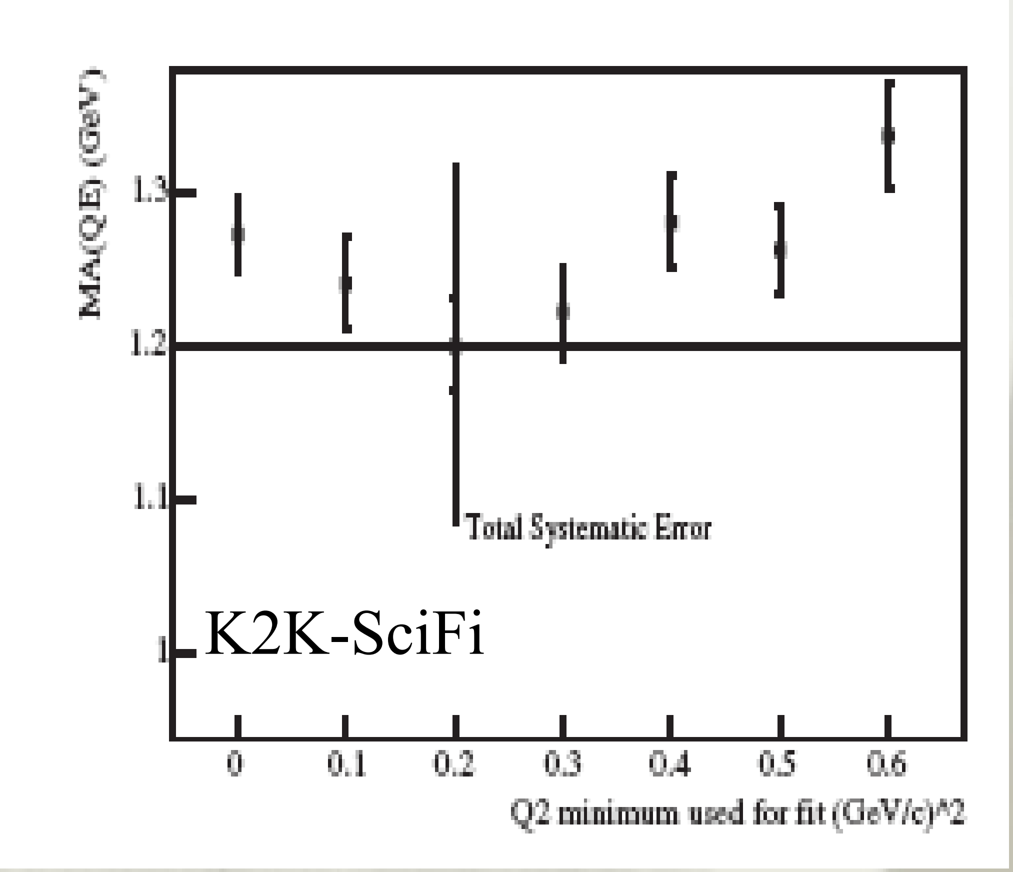
- Contribution to M_A from the different q^2 bins.



Systematic checks

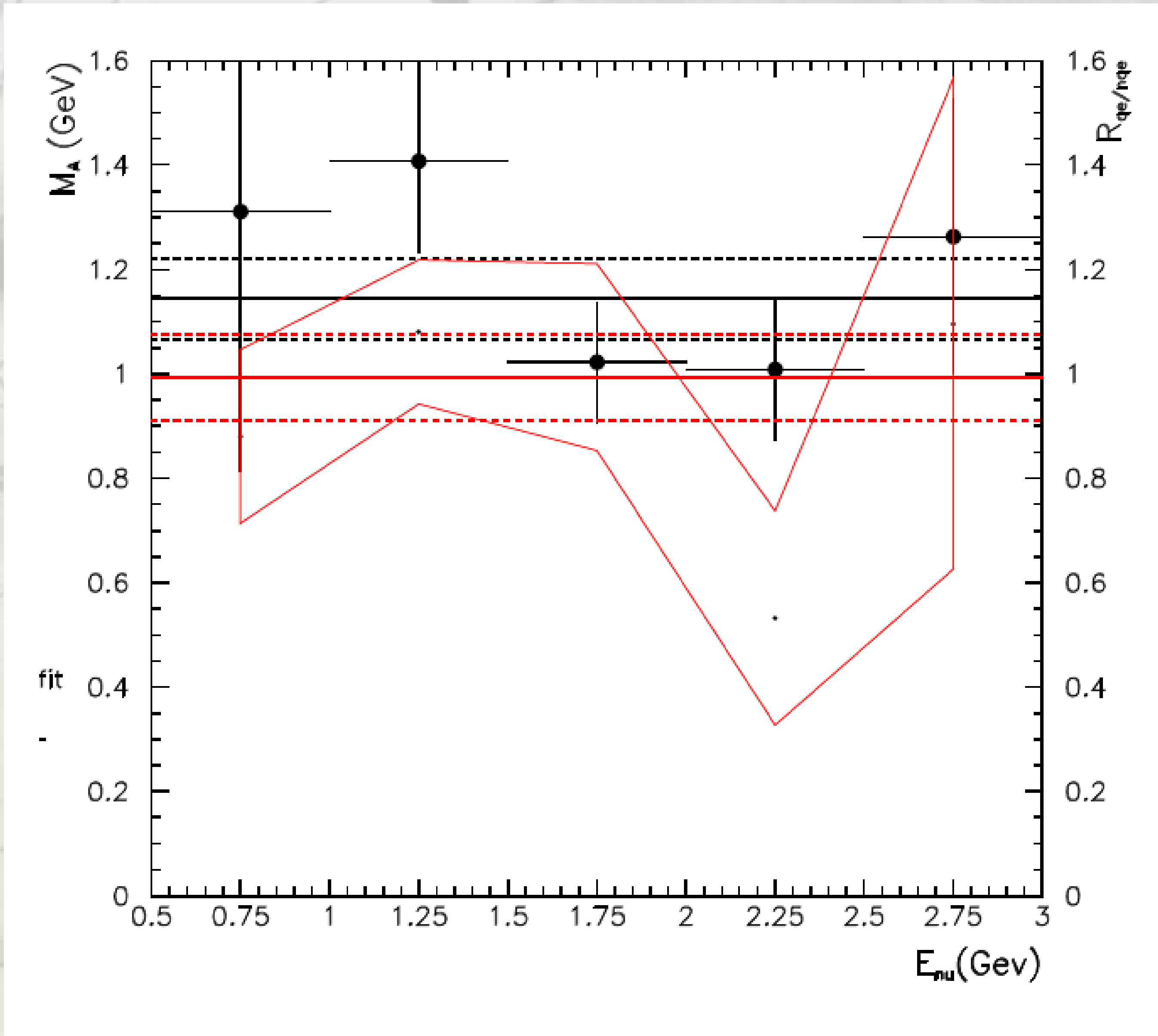
- Similar shape in K2K-SciFi. This could be an indication that the dipole approximation is incorrect.





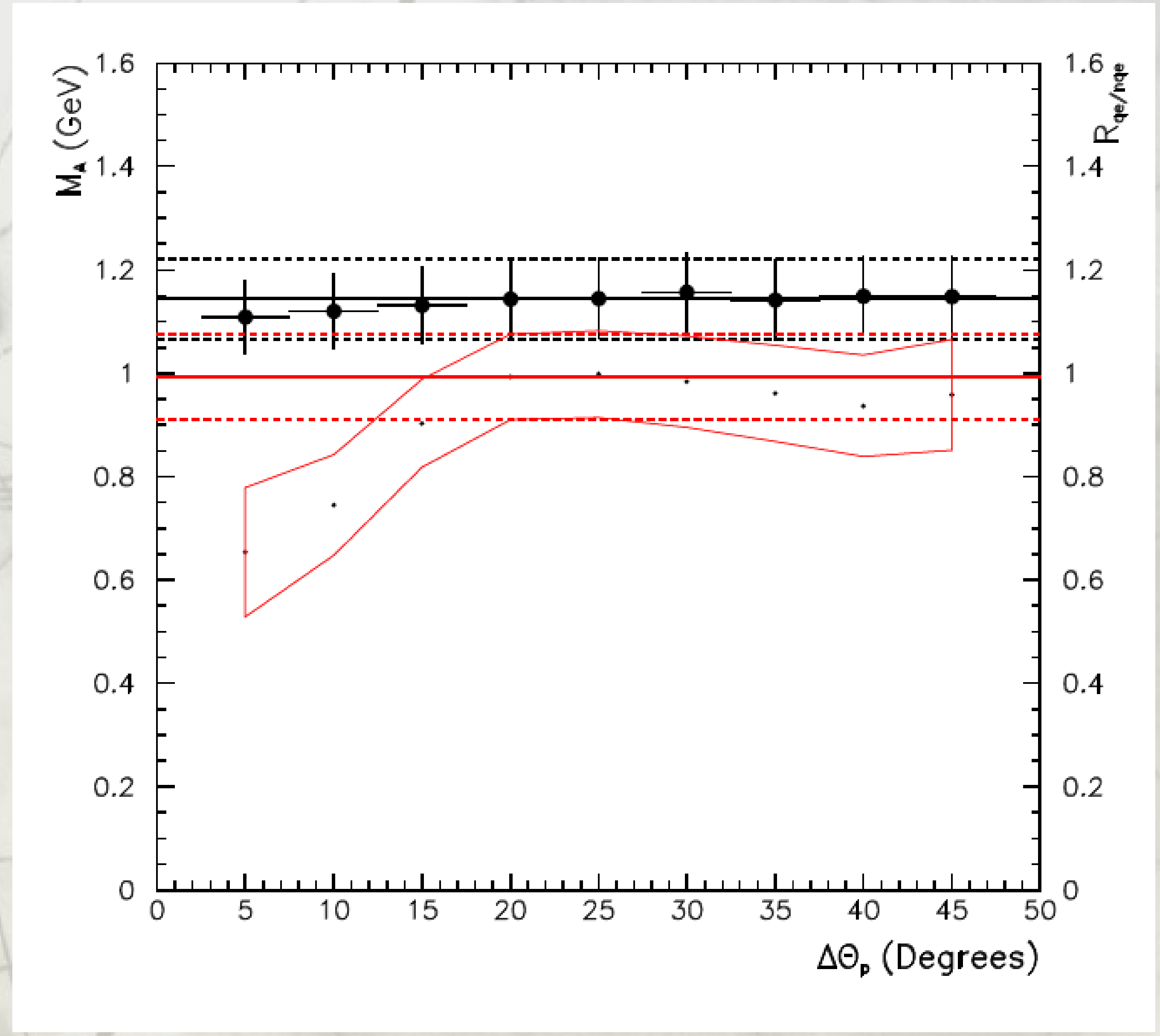
Systematic checks

- Contribution to M_A from the different energy bins.



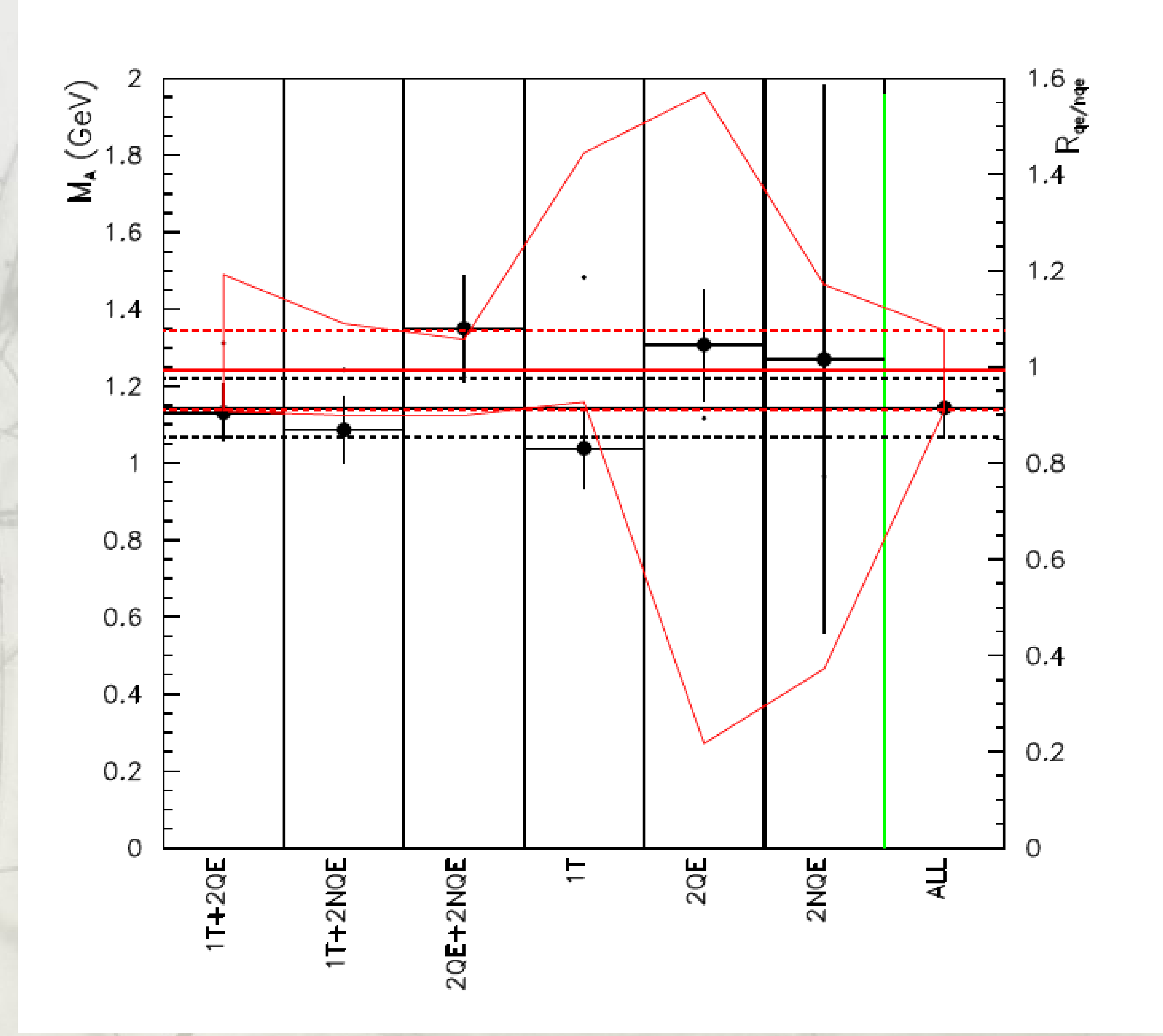
Systematic checks

- M_A as a function of the $\Delta\theta_p$ cut.



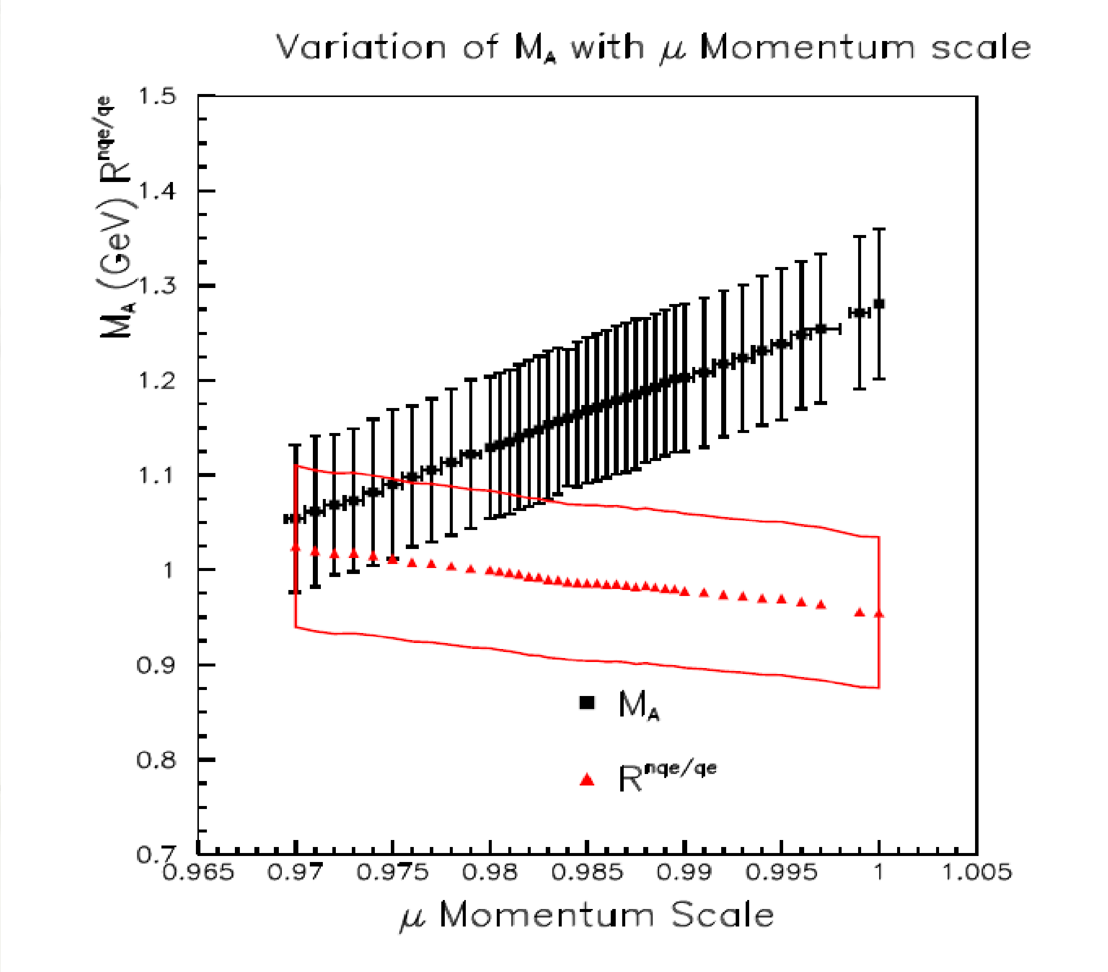
Systematic checks

- M_A for different samples.



Systematic errors: momentum scale

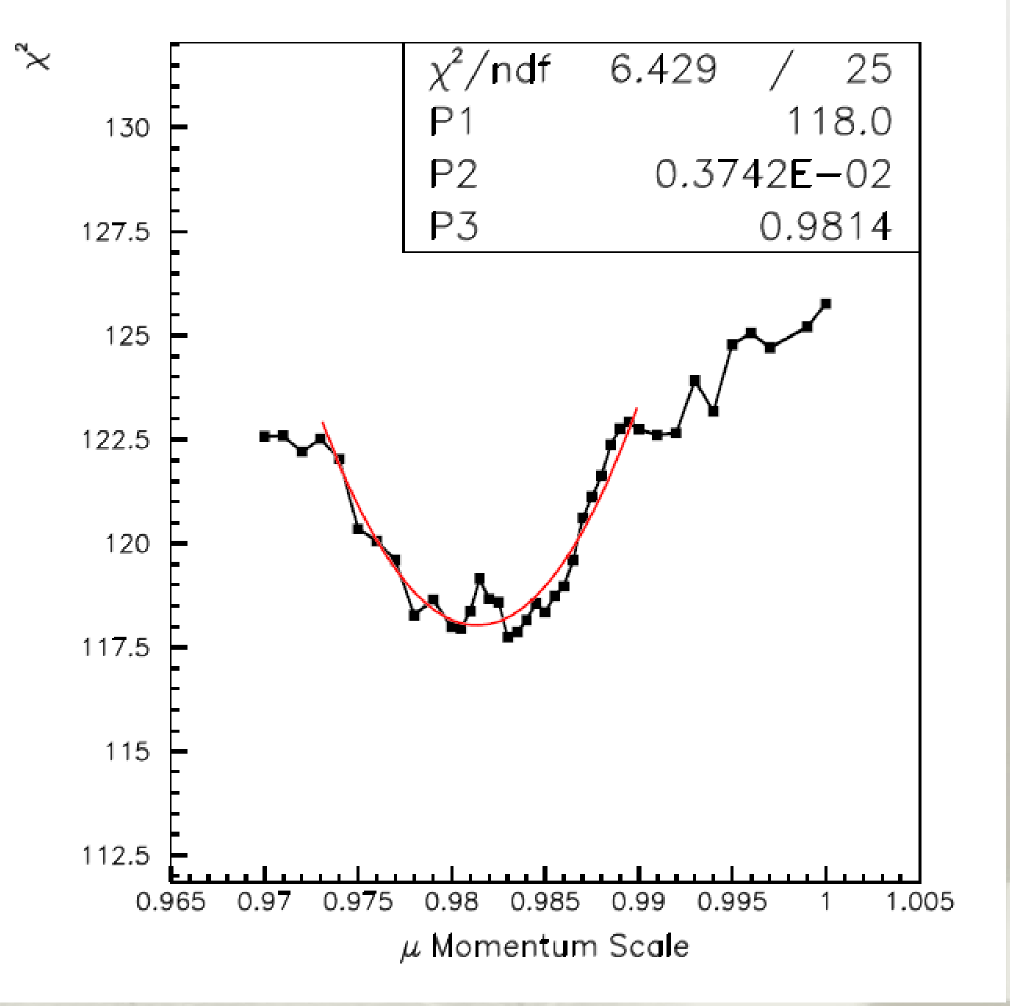
- MRD momentum scale is one of the parameters that influences the most the measurement of MA.



The main question is how to determine the right value for it.

Systematic errors: momentum scale

- We can represent the minimized value of the log-likelihood as a function of the momentum scale.
- The minimum is around 0.981, very close to the nominal result from global fit.



We take 0.981 as nominal with an error of 0.0037

Systematic errors

Sources of uncertainty	Error in M_A	Error in $R^{nQE/QE}$
$\sigma_{\Theta_{tracks}}$	-0.004	$+0.001$
$R_{2trQE/2trNQE}$	$^{+0.0}_{-0.01}$	$^{+0.0}_{-0.05}$
$\Delta\theta_p$	$^{+0.012}_{-0.036}$	$^{+0.0}_{-0.34}$
Total	$^{+0.012}_{-0.037}$	$^{+0.0}_{-0.34}$

Sources of uncertainty	σ_{M_A}	$\sigma_{R^{nQE/QE}}$
π Inelastic	$^{+0.011}_{-0.047}$	$^{+0.023}_{+0.044}$
p Rescattering	$^{+0.024}_{-0.022}$	$^{+0.050}_{-0.065}$
π Absorption	$^{+0.007}_{-0.010}$	$^{-0.017}_{+0.060}$
$M1\pi$	$^{+0.014}_{-0.010}$	$^{-0.028}_{-0.12}$
Bodek	$^{+0.007}_{+0.019}$	$^{-0.0043}_{-0.051}$
Coherent	$+0.013$	-0.024
Fermi motion	$^{+0.01}_{-0.01}$	$^{+0.021}_{-0.021}$
Total	$^{+0.035}_{-0.058}$	$^{+0.092}_{-0.15}$

Sources of uncertainty	Error in M_A	Error in $R^{nqe/qe}$
Quenching	$^{+0.012}_{+0.006}$	$^{-0.006}_{+0.021}$
X-talk	$^{+0.0005}_{-0.026}$	$^{+0.007}_{-0.0004}$
PMT Res.	$^{+0.012}_{-0.008}$	$^{+0.019}_{+0.007}$
Threshold	$^{+0.048}_{-0.006}$	$^{+0.11}_{-0.01}$
Total	$^{+0.051}_{-0.027}$	$^{+0.024}_{-0.030}$

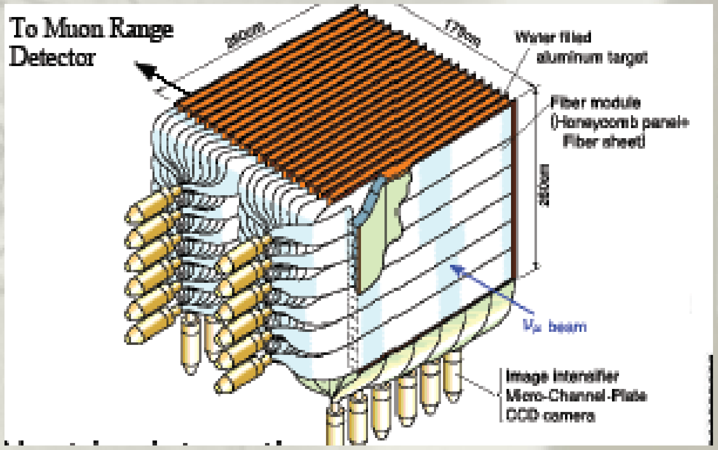
Sources of uncertainty	Error in M_A	Error in $R^{nQE/QE}$
Momentum Scale	$^{+0.030}_{-0.030}$	$^{+0.014}_{-0.014}$
Cross section and nuclear effects	$^{+0.035}_{-0.058}$	$^{+0.09}_{-0.15}$
Detector	$^{+0.051}_{-0.027}$	$^{+0.024}_{-0.030}$
Analysis	$^{+0.012}_{-0.037}$	$^{+0.0}_{-0.34}$
Total	$^{+0.078}_{-0.072}$	$^{+0.094}_{-0.37}$

SciFi CCQE MA Analysis

- Axial mass was also measured at the SciFi detector.

Phys.Rev.D74:052002,2006.

- Same to SciBar:
  - The analysis also make use of the q^2 shape.
  - It uses also BOSTED vector form factors.
  - Similar event classification and fitted parameters.
  - Similar treatment of nuclear effects
  - Similar systematic error contributions
- Different from SciBar:
  - The neutrino flux is not constrained
  - Oxygen vs Carbon target.
  - Different selection efficiencies.

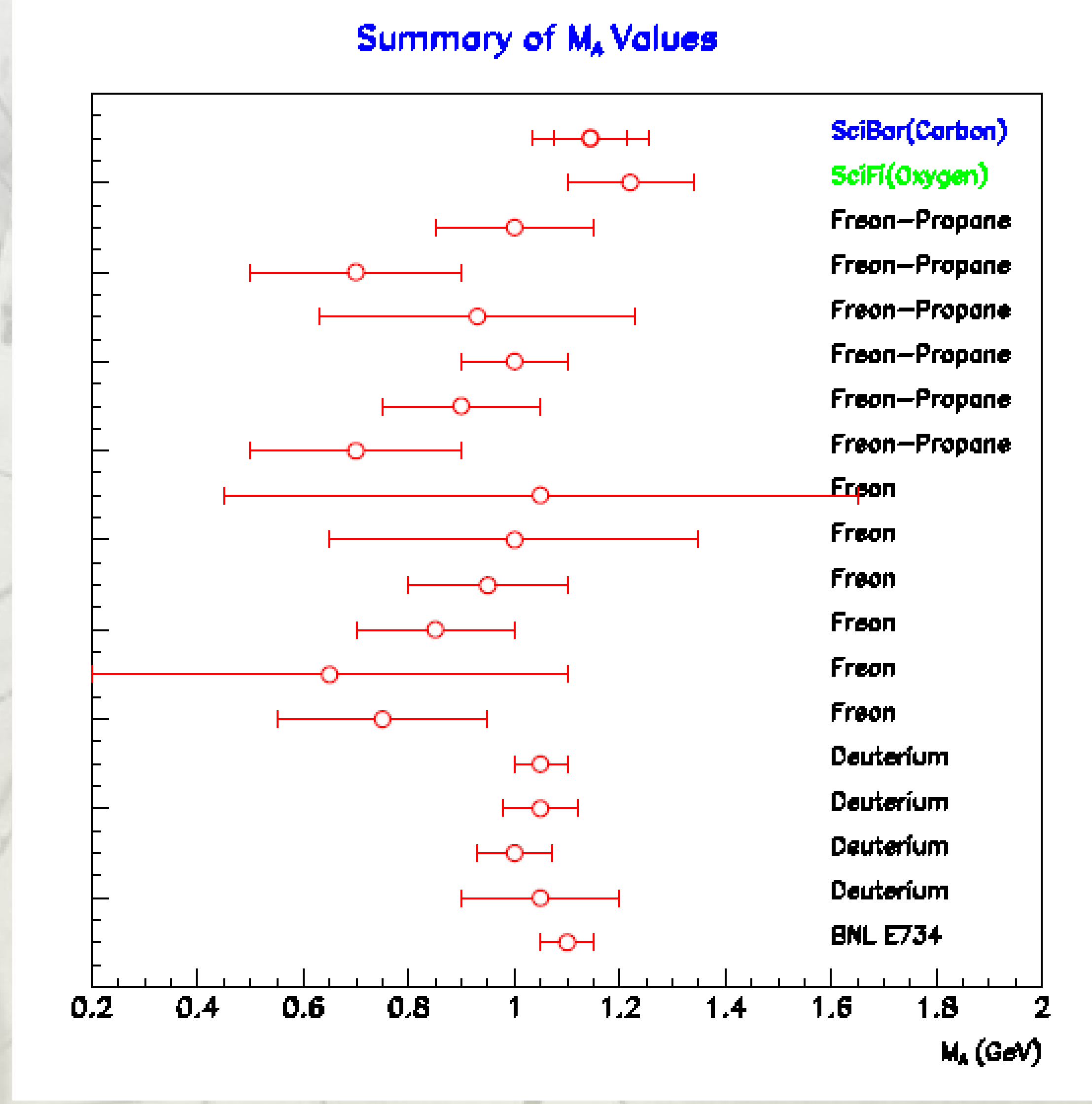


SciFi CCQE MA Analysis

- The SciFi result
  - $M_A = 1.20 \pm 0.12$ GeV (stat + syst)
- The SciBar result
  - $M_A = 1.144 \pm 0.077 \text{(fit)} {}^{+0.078}_{-0.072} \text{(syst)}$

SciFi and SciBar share many common systematic errors:
- Muon momentum scale.
- Nuclear rescattering.
- Flux uncertainties.
- ,,,

Results



- SciBar result is compatible with that of K2K-SciFi.
- It is larger than the values obtained in the past. Some of the old data was obtained with shape analysis and other with shape and cross-section. (see R.Gran talk).
- We have to take into account that shape and cross-section do not have to coincide since we are using the dipole approximation for the cross-section and q^2 and it doesn't have to be correct.

$$M_A = 1.144 \pm 0.077(\mathrm{fit}) + 0.078 - 0.072\ (\mathrm{syst})$$